SATELLITE PHOTOGRAPHS OF CONVECTIVE CLOUDS AND THEIR RELATION TO THE VERTICAL WIND SHEAR

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ABSTRACT

Several TIROS photographs of cumulonimbus clouds and thunderstorms over the Florida area are compared with synoptic surface and upper-wind data. The orientations of the cirrus anvils of well-developed clouds generally show good directional agreement with the existing vertical wind shears between the lower and upper troposphere. Limited evidence also suggests that the length and character of the anvils may sometimes be used as qualitative indicators of shear magnitude, the longer and more pronounced anvils being positively correlated with stronger vertical shear.

In agreement with earlier studies, it is found that cumulonimbus clouds often appear as relatively small or medium-sized, irregular, bright masses in TIROS pictures, hence such clouds often can be tentatively identified from their picture appearance alone. Such identification is still largely a subjective procedure. The anvils of well-developed cumulonimbi, when attached to the parent cloud, are rather distinctive and are an aid to identification.

A few TIROS pictures of the Florida area under relatively clear conditions are shown for comparative purposes. The problems arising from specular reflection and from variations in overall photo appearance resulting from changing camera angle are briefly discussed.

1. INTRODUCTION

Many observers have noted an apparent relationship between the structure of cumuliform clouds and the vertical shear of the wind field in which they are embedded. Relatively small cumulus clouds are observed to move with the wind and to lean in the direction of the vertical shear. Larger cloud towers lean in the direction of the shear, but usually to a lesser degree than the shear alone would indicate [1, 2, 14, 15]. In the case of certain large and vigorous thunderstorms, Hitschfeld [11, 12], Fujita [6], and Staff Members, NSSP [19], have presented evidence showing that the stems of such clouds tend to remain nearly upright, even in the face of strong vertical shear; and that the visible effect of the shear is mainly concentrated at the cirrus level, where large plumes or anvils emanate from the storm and are swept downwind.

Certain authors in the field of satellite meteorology have indicated that TIROS pictures of cumulonimbus and thunderstorm clouds may offer clues about the upper-level winds, although this idea has not been intensively pursued. Among these, a recent article by Fett [5] contains a fine example of cumulonimbus clouds in a field of considerable vertical shear, as seen by TIROS V over the South China Sea. The cirrus plumes are "carrot-shaped," pointing in the direction of the 200-mb. flow. Whitney [20, 21] and Whitney and Fritz [22] have pointed out that the severe-storm clouds of their studies tended toward elongation in the downstream direction of the upper-level winds. Fujita [6] and Fujita et al. [9] have used TIROS photographs together with radar and other data in their mesoanalyses of thunderstorms and likewise have found downwind elongation of the anvils. In one case investigated by them (May 27, 1960, over Florida [9]) they found that the anvils grew with the wind velocity at the cloud-top level for the first hour or so but grew at a slower rate thereafter. Other TIROS pictures of thunderstorm clouds have been correlated with surface data and have appeared in the literature [3, 4, 10], but the aspect of the clouds in relation to the wind field was not discussed in detail.

The purpose of this paper is to document a few TIROS satellite pictures of cumuliform clouds, particularly cumulonimbus and thunderstorms, with emphasis on the apparent relationship between the visual structure, as seen by TIROS, and the ambient wind field. The pictures were made over Florida and vicinity, where the surface observational network, at least over land, is relatively dense; furthermore, all pictures shown in this report were taken within 45 min. of the 1800 GMT synoptic hour. This permitted relatively good correlation in space and time between the surface observations and the cloud photographs. Rawinsonde data for 1200 and 0000 GMT were used to estimate the upper-air conditions at 1800 GMT.

Over vast areas of the Tropics and subtropics, knowledge of the three-dimensional wind field is often vague and sometimes almost nonexistent. It is not intended to imply that TIROS photographs are an adequate substitute for upper-wind reports, but it is shown that some information about the vertical structure of the wind field often

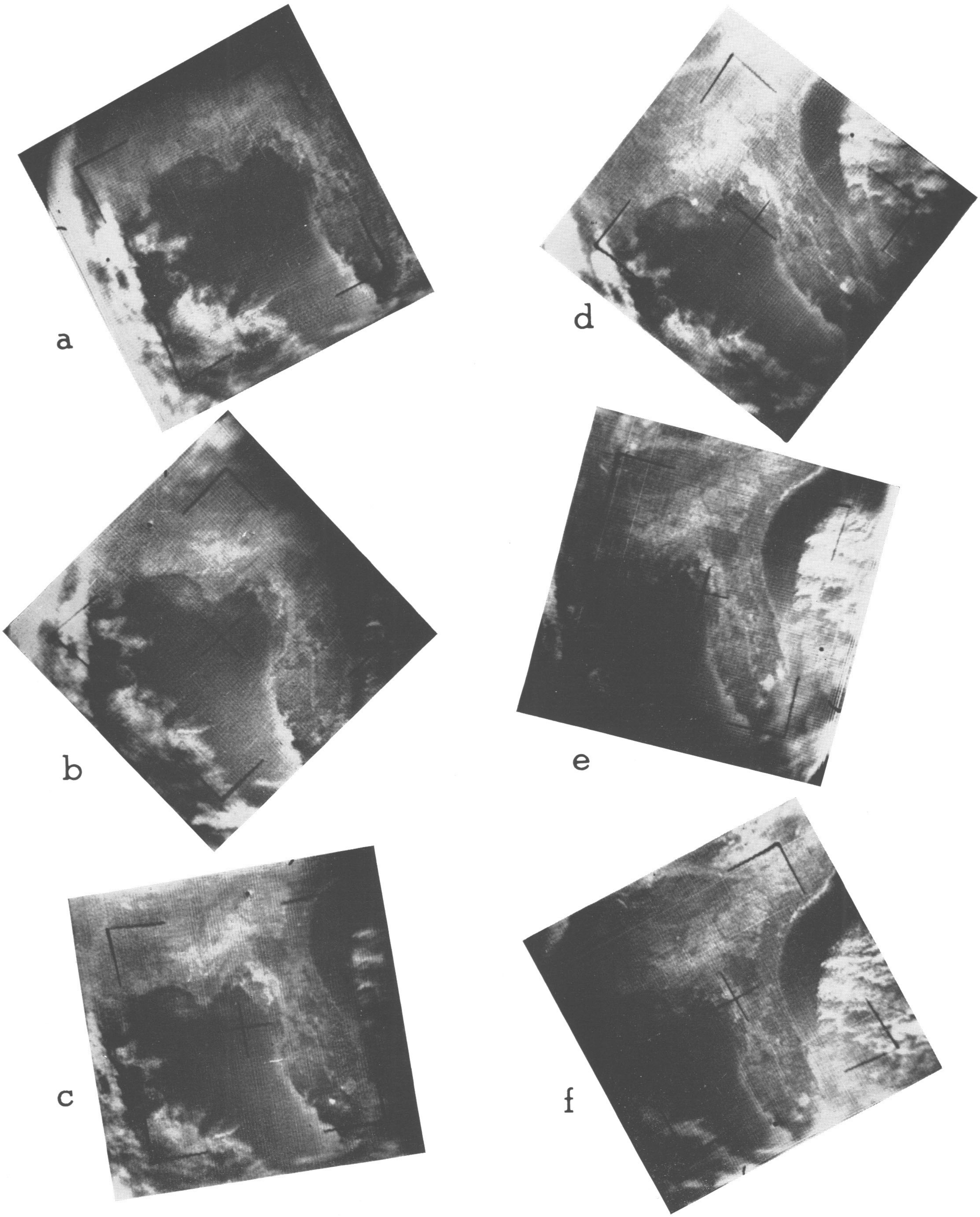

FIGURE 1.—TIROS IV photographs of Florida taken at 10-sec. intervals at approximately 1720 GMT, April 3, 1962. The pictures are from pass 778-direct and are arranged in chronological order, a through f.

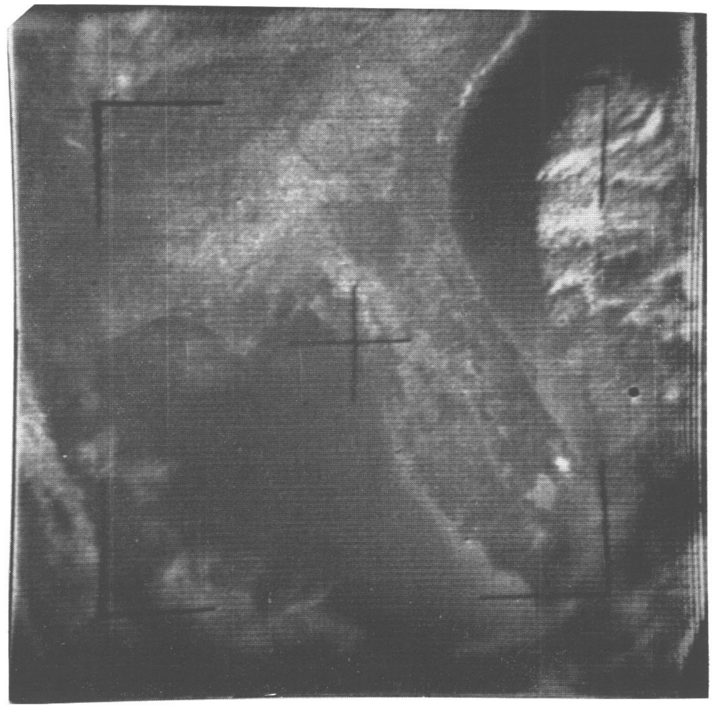

FIGURE 2.—Same picture as in figure 1e, enlarged. Time 1721 GMT, April 3, 1962.

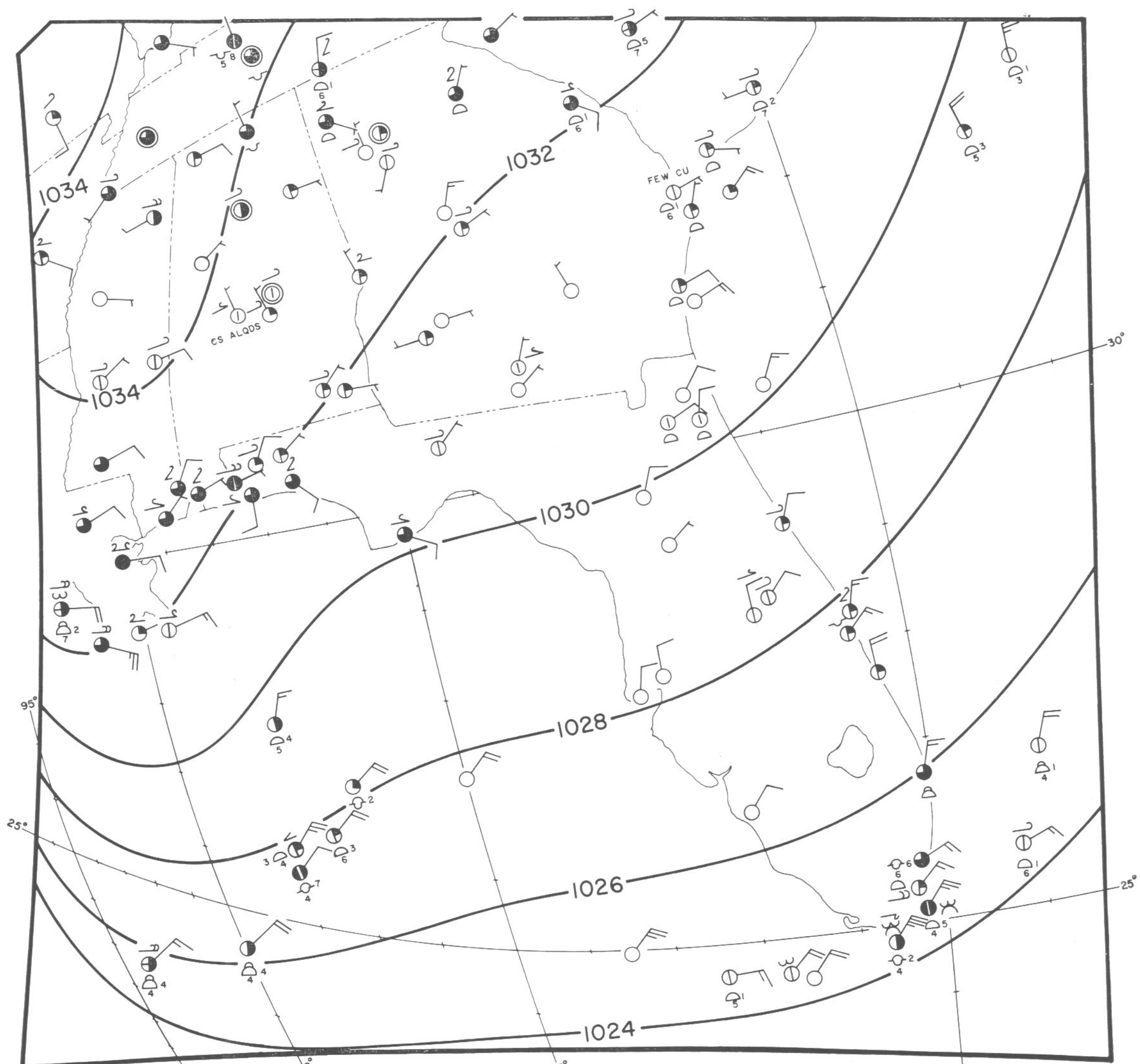

FIGURE 3.—Surface map for 1800 GMT, April 3, 1962, plotted on perspective grid to fit picture shown in figure 2. The plotted data include only sky cover, wind, clouds, and present weather.

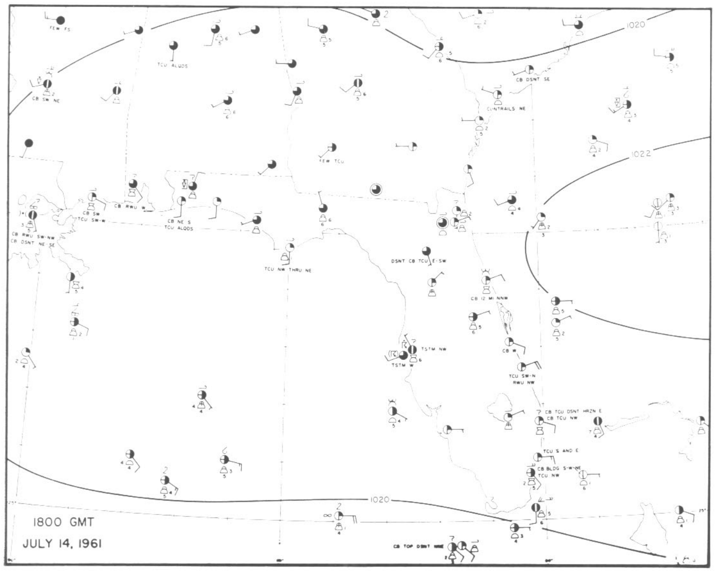

FIGURE 4.—Surface map for 1800 GMT, July 14, 1961, plotted on conventional (Lambert conformal) map base. The plotted data include only sky cover, wind, clouds, and present weather. Remarks pertaining to clouds and weather also are shown.

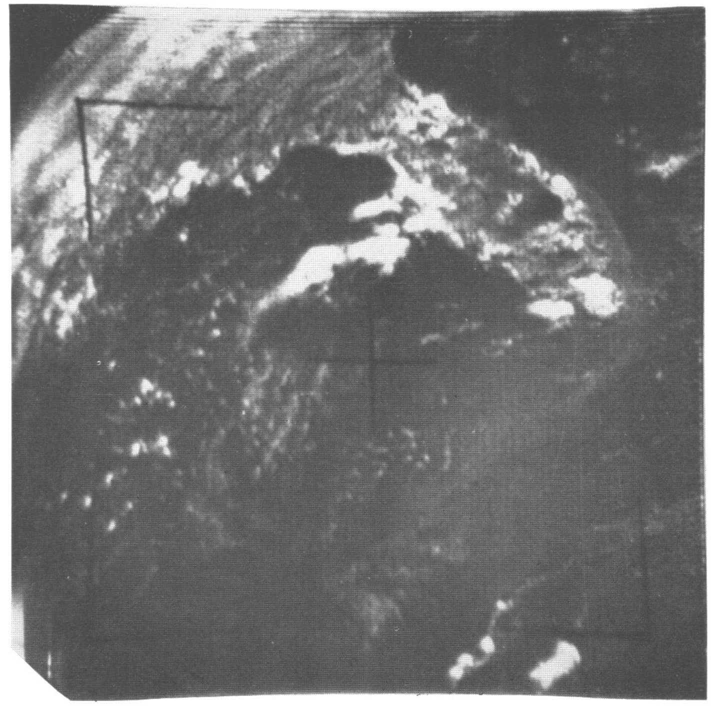

FIGURE 5.—TIROS III photograph (pass 033-direct, frame 20) taken at 1811 GMT, July 14, 1961.

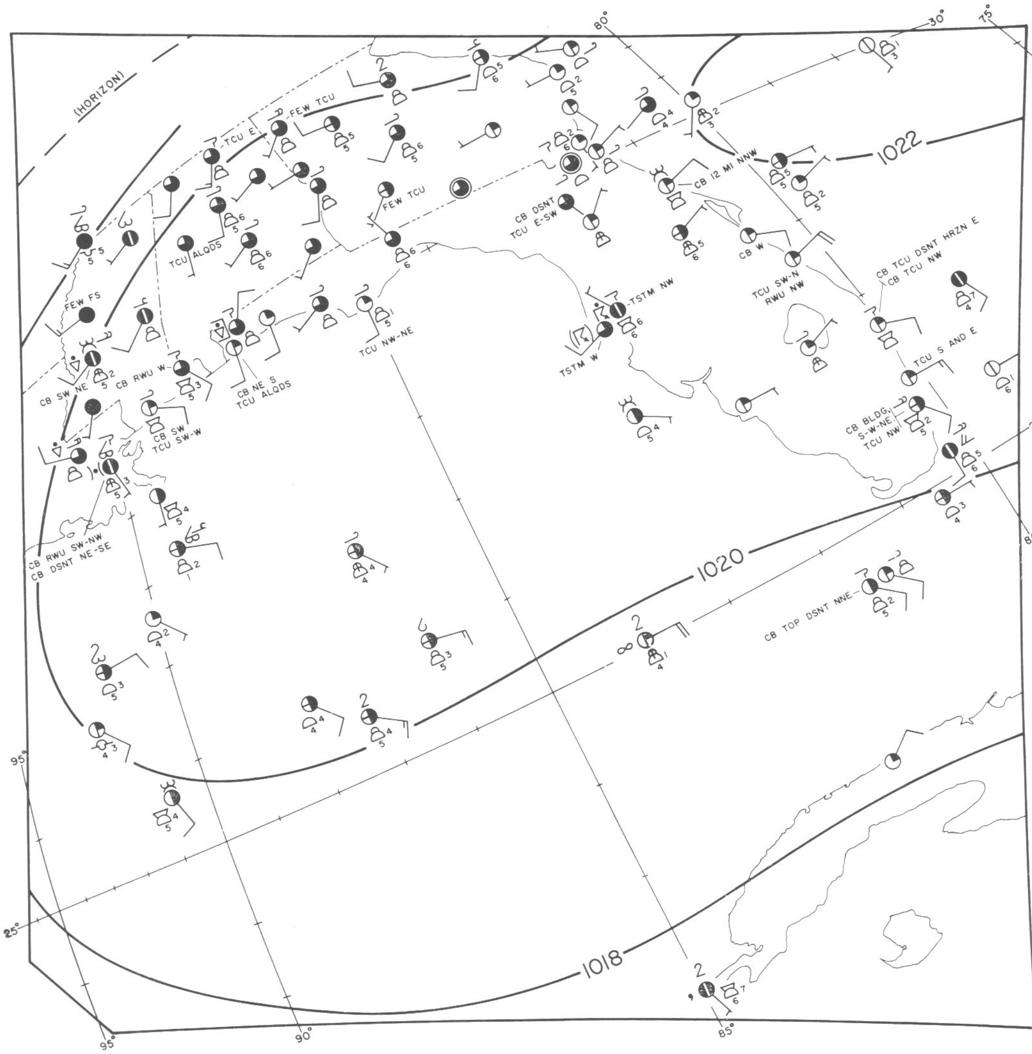

FIGURE 6.—Same data as in figure 4, plotted on perspective grid.

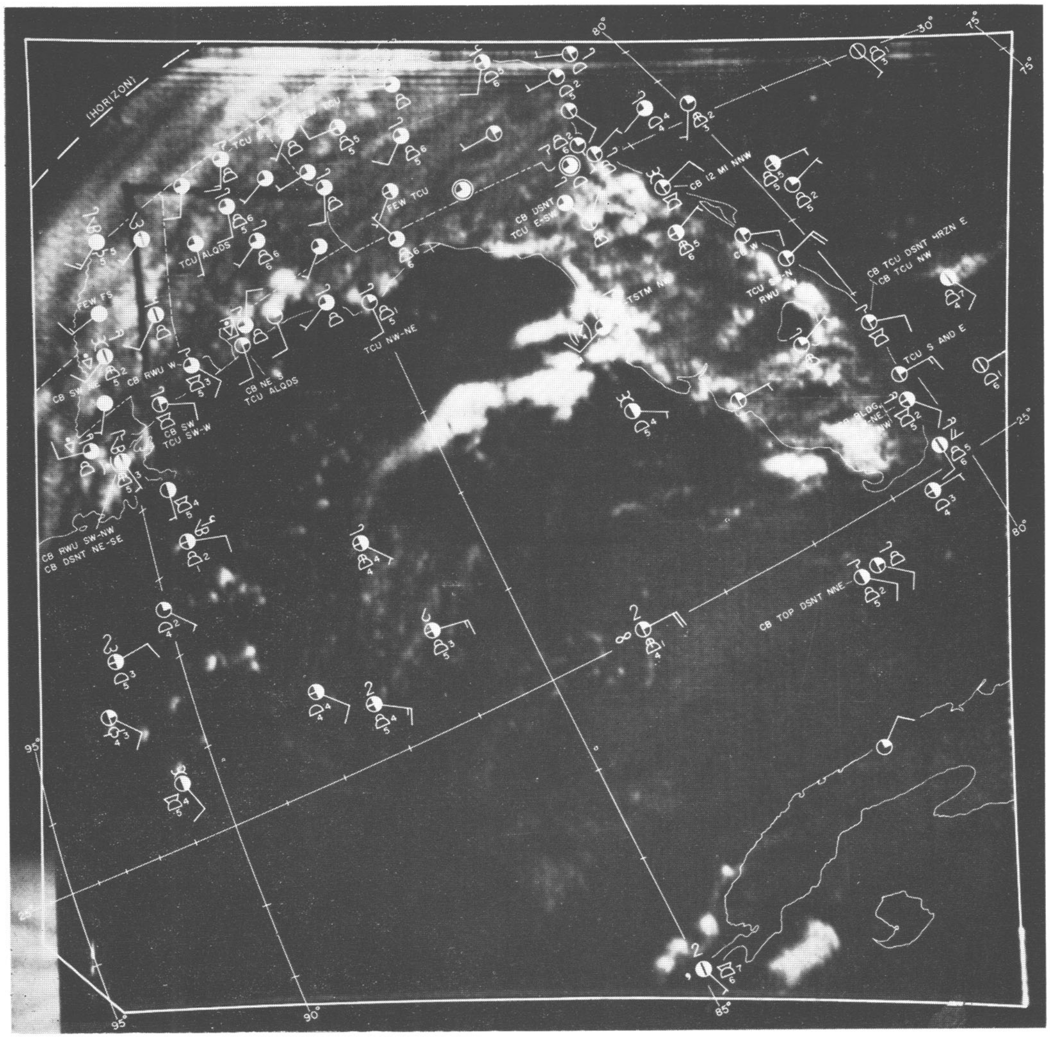

FIGURE 7.—TIROS III photograph taken at 1811 GMT, July 14, 1961, with plotted surface data for 1800 GMT. (Combination of figs. 5 and 6).

may be gained from TIROS photos. It is hoped that this may have some application in data-sparse areas.

2. CASE OF APRIL 3, 1962 A RELATIVELY CLEAR DAY

This particular situation is presented largely because it shows the appearance of the Florida area under relatively cloud-free conditions. Figure 1 contains six consecutive photographs from TIROS IV, pass 778-direct, April 3, 1962. The pictures were taken at 10-sec. intervals, at approximately 1720 GMT, and are arranged in chronological order, a through f. The local mean solar time at Miami was very nearly 12 noon. Figure 2 is an enlarged version of figure 1e, and figure 3 shows a portion of the surface synoptic analysis for 1800 GMT, including plotted data (winds, clouds, and present weather, only).

It is seen that the land area is comparatively clear, with thick cloudiness existing only over the Atlantic and the western Gulf of Mexico. An area of broken cirrus and cirrostratus exists along the Gulf Coast west of 85° W.; this shows up in the pictures as a relatively thin cloud mass. That portion of the cirrus over water is at least partially visible, but where there is an earth background it is very difficult, if not impossible, to see. Over the southern portions of Alabama, Georgia, and South Carolina, the scattered cirrus reported by ground observers is not discernible as such in the pictures, and the apparent shading over those regions probably represents land features. A line of cumuliform clouds is visible along the coast of South Carolina.

Other features of interest can be noted, such as the sharp western edge of the cloud mass over the Atlantic (perhaps related to the position of the Gulf Stream), but a discussion of such aspects is outside the scope of this paper. However, two final items, noticeable in figure 1, have rather general appplication to TIROS photo interpretation, and exert an influence in some of the other pictures of this study:

(1) The variation in relative brightness of the clouds

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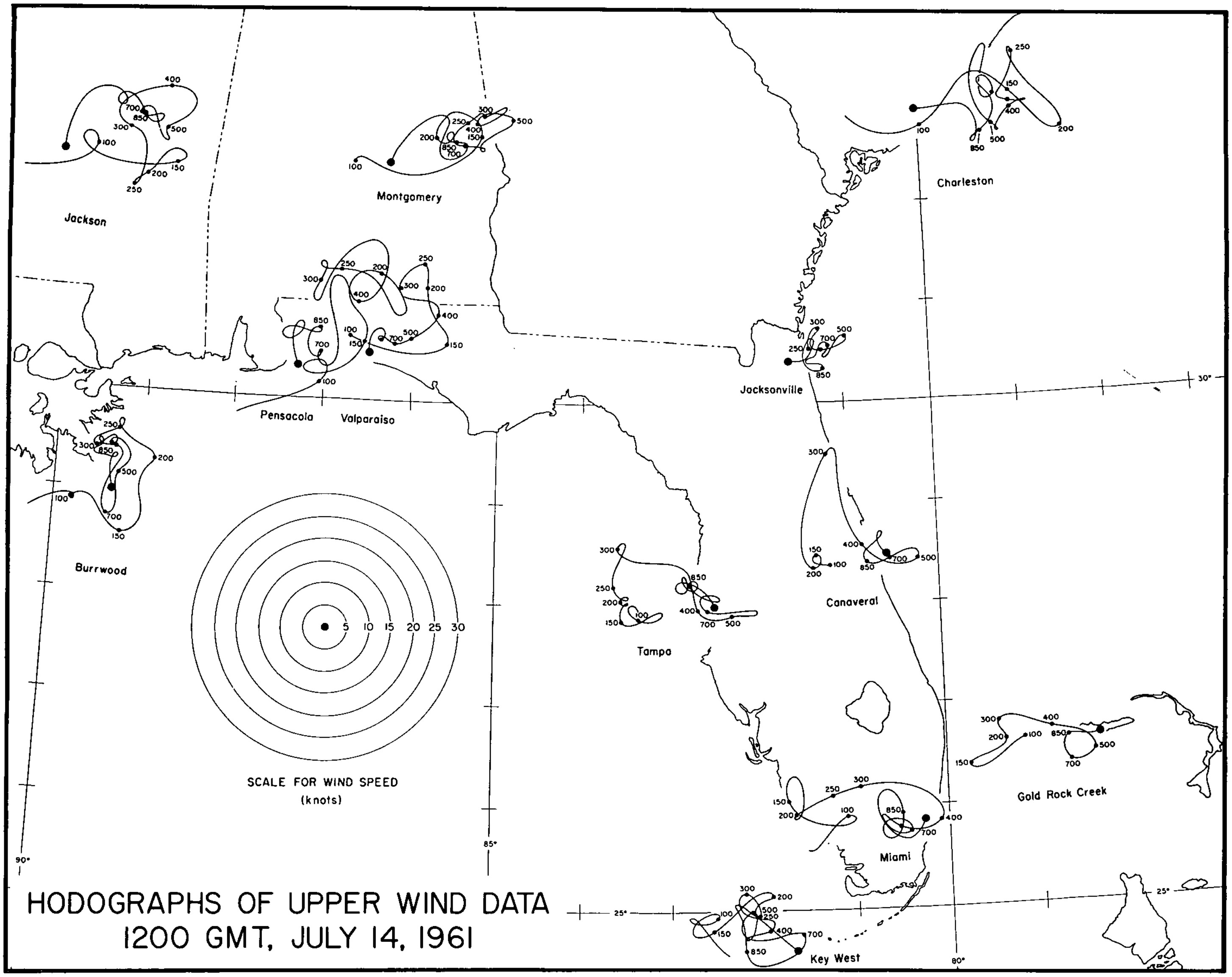


FIGURE 8.—Hodographs of upper-wind data for 1200 GMT, July 14, 1961. Small dots indicate standard millibar levels.

between different TIROS pictures. In figures 1a and 1b, the clouds over the western Gulf are relatively bright, while those over the Atlantic appear darker. In figure 1f, the situation is reversed, and the clouds over the Atlantic appear to be the brighter. The changing angle of the camera influences the brightness in TIROS pictures. The somewhat non-uniform response of the vidicon within the satellite is also a factor, because successive pictures of the same area are imaged in different orientations on the vidicon as a result of the spinning motion of the satellite. Other factors affecting the brightness also exist.

(2) The spot of specular reflection in figure 1, which marches across the lakes and swampy areas of southern Florida from southwest to northeast. Peninsular Florida, except for the lower east coast, was very nearly cloud-free at this time (see fig. 3), and the reflective area is visible in nearly every picture. In figures 1a and 1b it is near the west coast, then moves across the interior of southern Florida (c, d, and e), finally becoming a diffuse area of brightness over the wind-roughened waters off the east coast (f). Spots or areas of specular reflection often appear in over-water TIROS pictures at that point within the picture where the sun and the camera are at equal and opposite angles. Bright spots of specular reflection can sometimes be misinterpreted as cloud.

3. CASE OF JULY 14, 1961

Figures 4 through 7 are the combined presentation of a TIROS III picture taken at 1811 GMT, July 14, 1961, and the surface synoptic data and isobars for 1800 GMT. Although there is considerable redundancy in this presentation, it is obvious that each figure enjoys certain visual advantages not possessed by the others.

The grid overlay for figure 7 was prepared following the

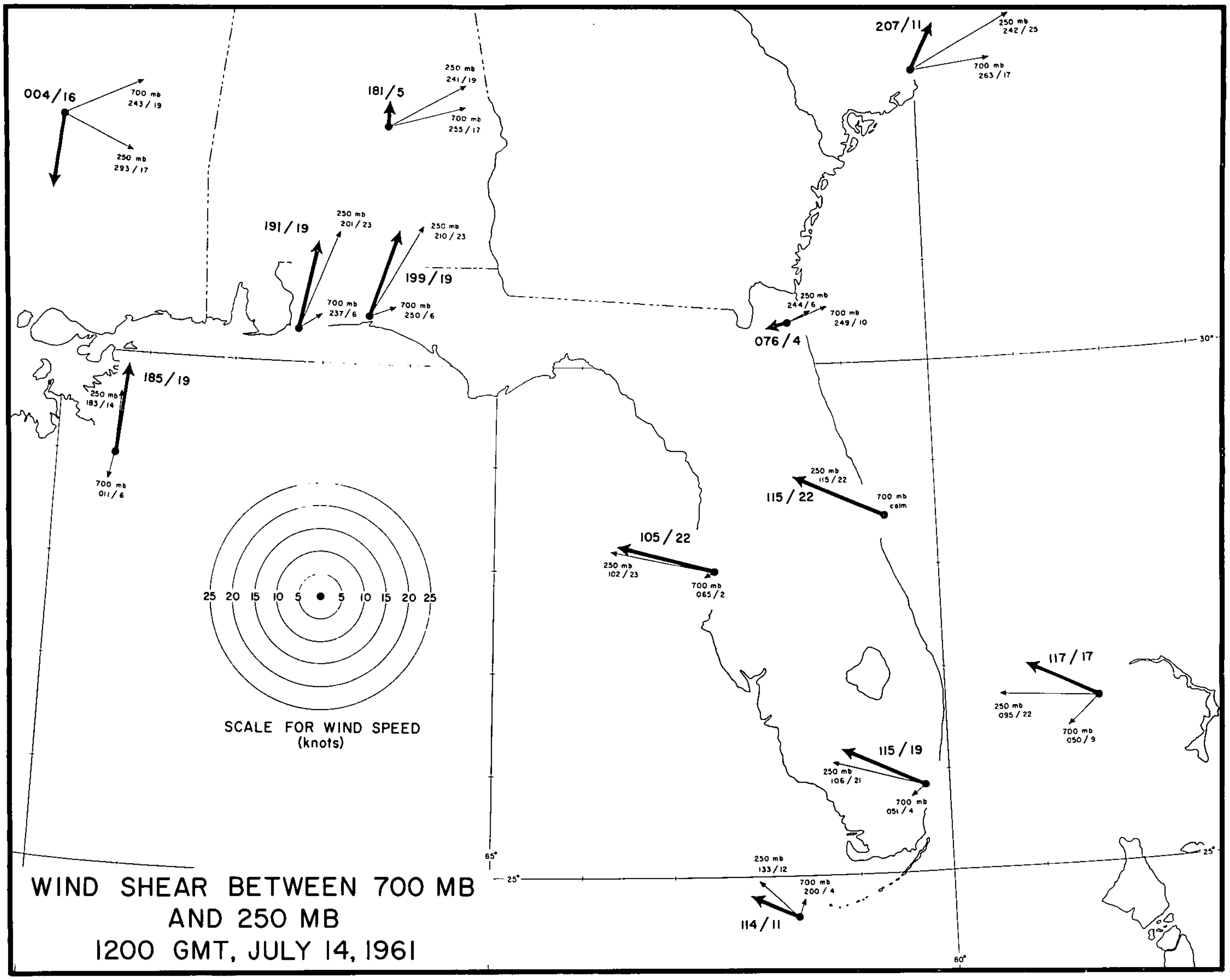


FIGURE 9.—Wind vectors at 700 mb. and 250 mb. (light arrows) and wind shear vectors for the 700–250-mb. layer (heavy arrows) for 1200 GMT, July 14, 1961.

graphical method developed by Fujita [7]. Some slight errors in the construction are apparent over western Cuba. The superimposed geography seems to be about 20 mi. east of where it should be on the photograph. However, the fit over Florida and over most of the remainder of the picture is quite good.

It can be seen from the plotted surface reports that the larger cloud "blobs" are mainly cumulonimbi. Other investigations [3, 4, 20, 21, 22] of TIROS pictures of cumulonimbus clouds and thunderstorms have established that such clouds tend to form in clusters and often appear as bright irregular blobs surrounded by relatively clear air, or as splotchy cloud masses with relatively abrupt gradations in brightness.[1] Even the smaller apparent cloud elements in this picture probably are clusters of swelling cumuli or small cumulonimbus clouds; and a region of predominantly fair-weather cumuli, such as that over southern Georgia, is largely devoid of cumuliform appearance, the cloud elements there being mostly too small to be individually resolved [4].

Hiser et al. [10] have also investigated this particular photograph, correlating the cloud images with WSR–57 radar data from Tampa. They found that the precipitation echoes generally were contained within the brighter cloud masses, but the total area occupied by echoes was much less than that occupied by the cloud masses. Some of the brighter masses contained no echoes.

Figure 8 shows the hodographs of upper-wind data for 1200 GMT. Although this is 6 hours before the time of the

[1] The size range of thunderstorm clouds, as seen in TIROS pictures, covers almost the whole mesoscale spectrum. Small isolated cumulonimbi may be only 3–10 mi. in diameter; however, most thunderstorms seem to be associated with clusters of cumulonimbi which appear in TIROS pictures as blobs or small masses, generally 10–100 mi. in diameter. Studies by Whitney [20, 21] and Whitney and Fritz [22] deal with the larger sizes of cumulonimbus clusters—those more likely to produce severe storms. Those are of the order of 100–200 mi. in diameter.

picture, there is good agreement between the general east-to-southeast flow over lower Florida and the apparent westward propagation of the clouds relative to the peninsula (see fig. 5). Along the lower east coast, the westward displacement of the clouds doubtless is aided by the sea-breeze effect, which would not have been reflected in the 1200 GMT winds of figure 8. At Miami, for example, the lower-level flow at the time of the picture probably was more strongly from the east than it was 6 hours earlier (fig. 8).

In addition to the apparent westward propagation of the clouds relative to the lower peninsula, the larger cumulonimbi reveal evidence of vertical shear, with their tops seeming to lean toward the west. The thunderstorms west of Tampa have large cirrus anvils extending westward. This is in agreement with the generally stronger easterly flow above the 300-mb. level over Tampa. The height of the anvils is not definitively known, but they almost certainly emanate from levels mainly above the 300-mb. level and occupy at least a few thousand feet in the vertical dimension.

In contrast to conditions over lower Florida, the cumulonimbi between Daytona Beach and Jacksonville reveal no evidence of westward movement away from the coast, or of vertical shear; and the upper winds over Jacksonville are likewise in agreement, being very light at all levels. The surface winds at the three Jacksonville stations (located 10 to 30 mi. inland) remained light and variable until after 2000 GMT, indicating that the sea breeze in that area had at most penetrated only a short distance inland at the time of the picture. Presumably, therefore, the sea breeze had exerted no great influence on the clouds in that area prior to that time.

Because the picture was taken at 1811 GMT, almost midway in time between the 14/1200 GMT and 15/0000 GMT rawinsonde observations, one might ask why not, with equal justification, use the 15/0000 GMT data, or better yet, the combined data for both hours. This was not done in this case because the overall flow pattern was rather stable, showing little change between the two synoptic hours. Furthermore, it could be argued that the cloud structures existing at 1811 GMT are the result of cumulative processes occurring over a period of time prior to 1811 GMT, and that the 1200 GMT observations should therefore be given more weight than the 0000 GMT observations (assuming linear changes between the two hours). For these reasons, only the 1200 GMT data are shown here, and it is believed that they are reasonably representative of conditions prior to 1811 GMT, with the exception of the diurnal sea breeze noted earlier.

Among previous investigators concerned with the displacement of large convective clouds, Ligda [13] and Newton and Katz [17] found a high correlation between the movement of radar echoes of cumuliform precipitation and the 700-mb. flow. Byers and Braham [2] determined that the echoes of their study moved in the direction of the vector mean wind between the gradient level and 20,000 ft., but that they tended to move more slowly than the mean wind. Newton and Katz [17] and Newton and Newton [18] found that while individual echoes tended to move with the mean wind, there was a systematic deviation in the movement of large convective rainstorms of 20° to 25° to the right of the mean wind direction. This they attributed to propagation, or growth of new cells.

As a first approximation, it is convenient to assume that the cumulonimbus cloud is moving with the 700-mb. wind. Since the lower tropospheric winds are generally rather light through a relatively deep layer in the cases discussed here, the errors in this assumption should be small. Likewise, it is assumed that the cirrus plumes emanating from the tops of cumulonimbus clouds are moving with the wind at that level and are relatively unaffected by lower-layer currents. Following this reasoning, the orientation of the anvil clouds in TIROS photographs should be indicated by the shear vector between 700 mb. and the cirrus level.[2] For the case of July 14, 1961, this is given in figure 9. The mean pressure of the cirrus level is estimated to be near 250 mb.

It is seen that the shear vectors over southern Florida in figure 9 are closely aligned with the orientation of the cirrus plumes over the same area in figure 5. Farther to the northwest, along the Gulf Coast, the situation is less well-defined. Although cumulonimbi are reported at coastal stations from Pensacola westward, there are no noticeable anvil extensions in any particular direction despite the moderate southerly shear between 700 mb. and 250 mb. over that area. The clouds appear to be smaller and less well-developed than those over peninsular Florida, and it is entirely possible that the anvils were only beginning to form. It is also possible that the 700–250-mb. vertical shear is not sufficiently representative of the more chaotic nature of the complete vertical wind profile over that area (see fig. 8). Either or both of these factors may have contributed to the lack of noticeable anvil extensions over the Pensacola-New Orleans region.

In the cumulonimbus clouds of this study, it is likely that there is a tendency for those clouds over land but near coastlines to remain rooted to the low-level sea-breeze convergence that helped to produce them. Clouds originating over such topographically favorable locations would have a tendency to remain stationary and to propagate upstream relative to the mean wind; and the cirrus plumes from such clouds should coincide more nearly with the upper-level wind itself than with the shear.

Because the 700-mb. flow over Florida is quite light in this case, there is little difference between the shear vector and the 250-mb. wind vector at individual stations, and it is not possible to say whether the orientation of the cirrus plumes agrees better with the shear or with the 250-mb.

[2] Fujita [8] has employed a similar technique in his investigation of cumulonimbi associated with a tropical storm over the South Pacific. He found that the direction of the anvils agreed very well with that of the geostrophic shear between 700 mb. and 300 mb.

wind itself, because there is no significant difference between them.

4. CASE OF AUGUST 19-21, 1962 [3]

This 3-day period begins with the existence of a rather broad and not too well defined zone of cumulonimbi and showers aligned ENE-WSW across central Florida and adjacent waters (see pictures, fig. 10 [4]). The surface map (fig. 11) reveals a weak pressure pattern, with generally light easterly or southeasterly flow. The plotted data of figure 11 also indicate the concentration of convective activity in the east-west zone around 28° N., but with scattered cumulonimbus clouds both north and south of this zone.

The general appearance of the clouds in figure 10 indicates no great amount of vertical shear in the main zone of convective activity. This is supported by the shear chart for the layer 700-200 mb. (fig. 12), which shows that both the shear and the winds themselves are very light across central Florida. However, in the area west of Tampa it is possible to see a feathering out of the cirrus eastward, in agreement with the light westerly shear existing over Tampa. Likewise, in the cloud masses west and east of Jacksonville there appear to be cirrus extensions toward the east-northeast, in agreement with the directional shear over that area.

In this case of August 19-21 the 200-mb. surface was chosen to represent the cirrus level, partly because of slightly greater instability and a higher tropopause than on July 14; but again there is not definite knowledge of the mean height of the cirrus. Both the winds and the shear in figure 12 are vector means of the observations from the two upper-air synoptic hours bracketing the picture time.

On the next day, August 20, the broad zone of cumulonimbi and showers continues in an alignment roughly ENE-WSW across central Florida. The two TIROS pictures of figure 13 show that the ENE-WSW concentration of clouds extends for considerable distances over the water areas on either side of Florida. The plotted surface data for figure 14, while failing to reveal the complete areal cloud distribution, do indicate several thunderstorms along the Florida east coast and some showers and squalls at ships well removed from the coast, providing additional evidence that the ENE-WSW cloud zone is in fact largely cumulonimbi and showers. The complementary nature of satellite and conventional data is well illustrated here.

[3] Merritt [16] shows two TIROS photographs taken on August 20 and 21 (his figs. 3 and 5, respectively) which are not the same as the ones reproduced in this report but which are from the same TIROS passes and cover much of the same area. He confines his discussion to the clouds near Cuba and the Florida Keys, associating them with a weakened easterly wave in that area.

[4] The geographic overlays to figure 10 and subsequent picture pairs were derived from latitude-longitude grids produced by the 7090 computer. The geography was hand drawn to agree with the grid lines, and the composite overlay then matched with the picture using an overall best-fit technique. Some slight discrepancies may be noticed in the location of features common to both frames of a pair, but the overall fit appears to be reasonably good in all cases.

The pictures of figure 13 display some evidence of an organized pattern in the vertical shear. In frame 6 (left) the clouds over the central Gulf of Mexico appear to be sheared off toward the north and northeast, while the clouds over the Atlantic in frame 7 (right) have plumes extending southeastward and southward. The overall pattern of the vertical shear is anticyclonic (in the horizontal sense), and is centered roughly over the eastern Gulf of Mexico. The shear chart (fig. 15) shows striking agreement with this overall pattern. The only noticeable exception appears to be near Miami where the northwesterly shear does not agree with the apparent cloud structure south of Lake Okeechobee. That particular cloud appears to be feathered off toward the southwest, more nearly in agreement with the actual 200-mb. flow than with the shear; this would be expected if the cloud were tending to remain stationary due to local effects.

The pictures of figure 13 also illustrate the possible confusion between specular reflection and cloud. In the picture on the right (frame 7), Lake Okeechobee could easily be mistaken for a cumulonimbus cloud (compare with frame 6 taken only 30 sec. earlier). Also, in frame 7, there is a small, very bright spot just northwest of Lake Okeechobee which likewise did not appear in frame 6. That bright spot probably is a swampy patch of the Everglades.

Figures 16 through 18 show the situation on August 21. The two TIROS pictures for this day (fig. 16) are located somewhat southeast of their counterparts on the previous day, while the ENE-WSW zone of cumulonimbi and showers has moved northward and weakened. Consequently, only a fringe of that zone now is seen, it being located across the northern edge of frame 5 (right).

Figure 18 indicates relatively strong northerly shear in the region between southern Florida and Cuba. The orientation of the large cirrus plumes in the corresponding areas of the pictures of figure 16 shows good agreement with this; furthermore, the character of the plumes—their long feathery southward projections as contrasted with the bright sharp-edged northern boundaries of the parent cumulonimbi—gives one the definite impression of relatively strong shearing action toward the south. Admittedly, such inferences about the magnitude of the vertical shear must necessarily be very qualitative and subjective, but it is important to note that these inferences sometimes can be made. Fett [5] and Fujita [6] have also shown examples of TIROS pictures of cumulonimbi embedded in fields of relatively strong vertical shear.

In frame 3 of figure 16, there also is good agreement between the orientation of the plumes over Jamaica and vicinity and the quite different westerly shear over Jamaica and Guantanamo, Cuba, shown in figure 18. Unfortunately, these clouds over Jamaica and southward are seen much less clearly here in figure 16 than in the original film strip.

In both regions (the Jamaica area and western Cuba), it could be argued that the cloud orientation agrees equally

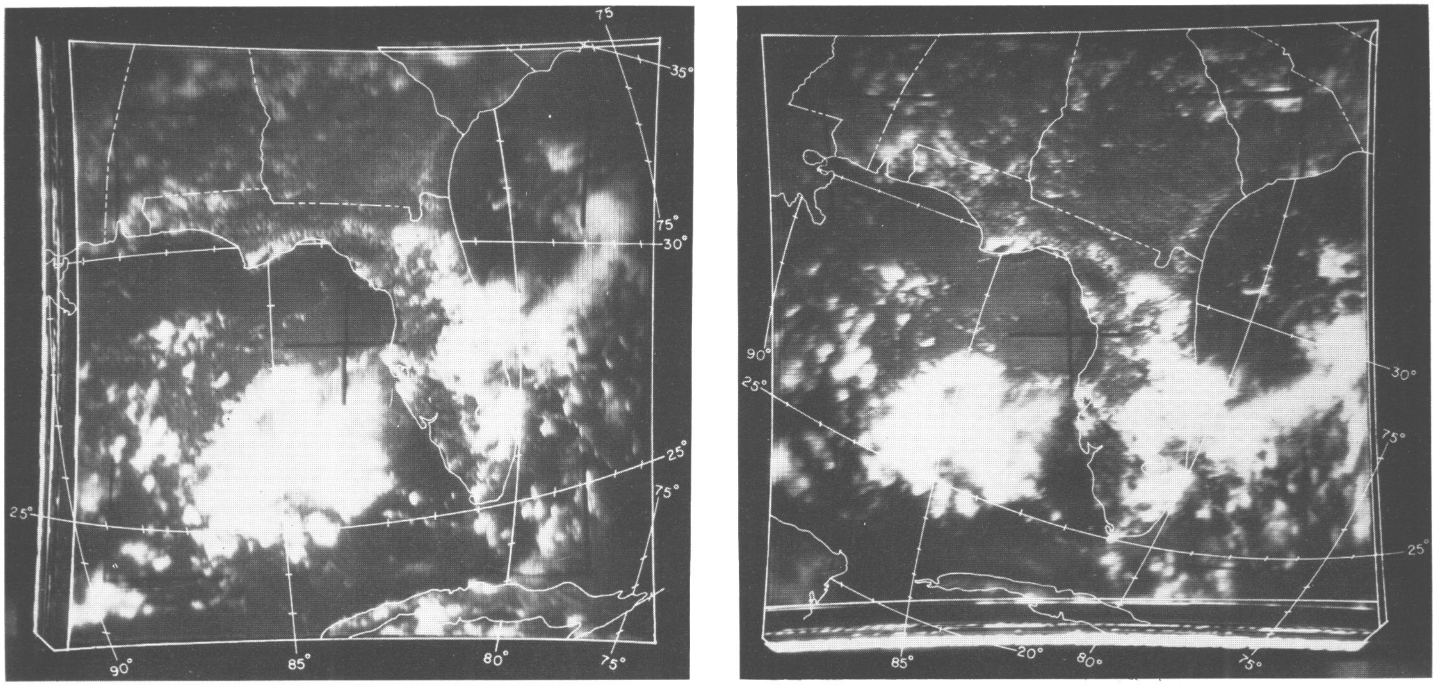


FIGURE 10.—TIROS V photographs (pass 878/877, frames 7, left, and 6, right) taken at approximately 1824 GMT, August 19, 1962.

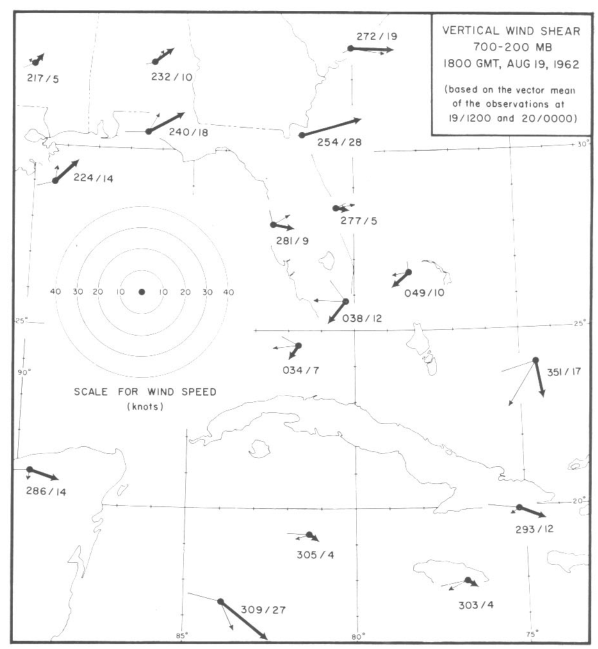


FIGURE 12.—Vectors for the 700-mb. wind (light lines), 200-mb. wind (light arrows), and the vertical shear for the 700–200-mb. layer (heavy arrows) for 1800 GMT, August 19, 1962. All vectors are vector means of the observations at 19/1200 GMT and 20/0000 GMT.

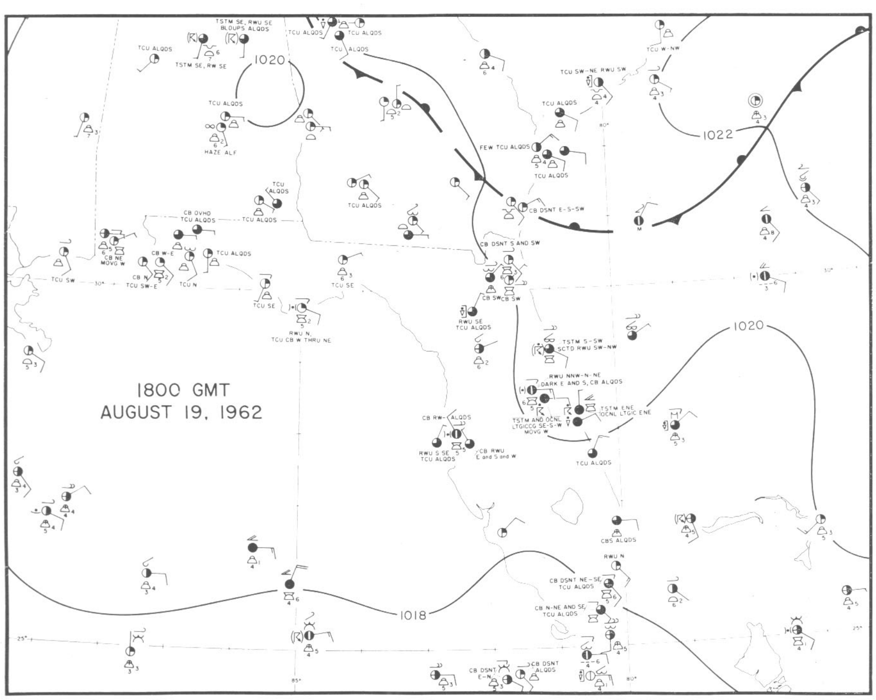


FIGURE 11.—Surface map for 1800 GMT, August 19, 1962, including sea level isobars and plotted data (sky cover, wind, clouds, and present weather). Remarks pertaining to clouds and weather also are shown.

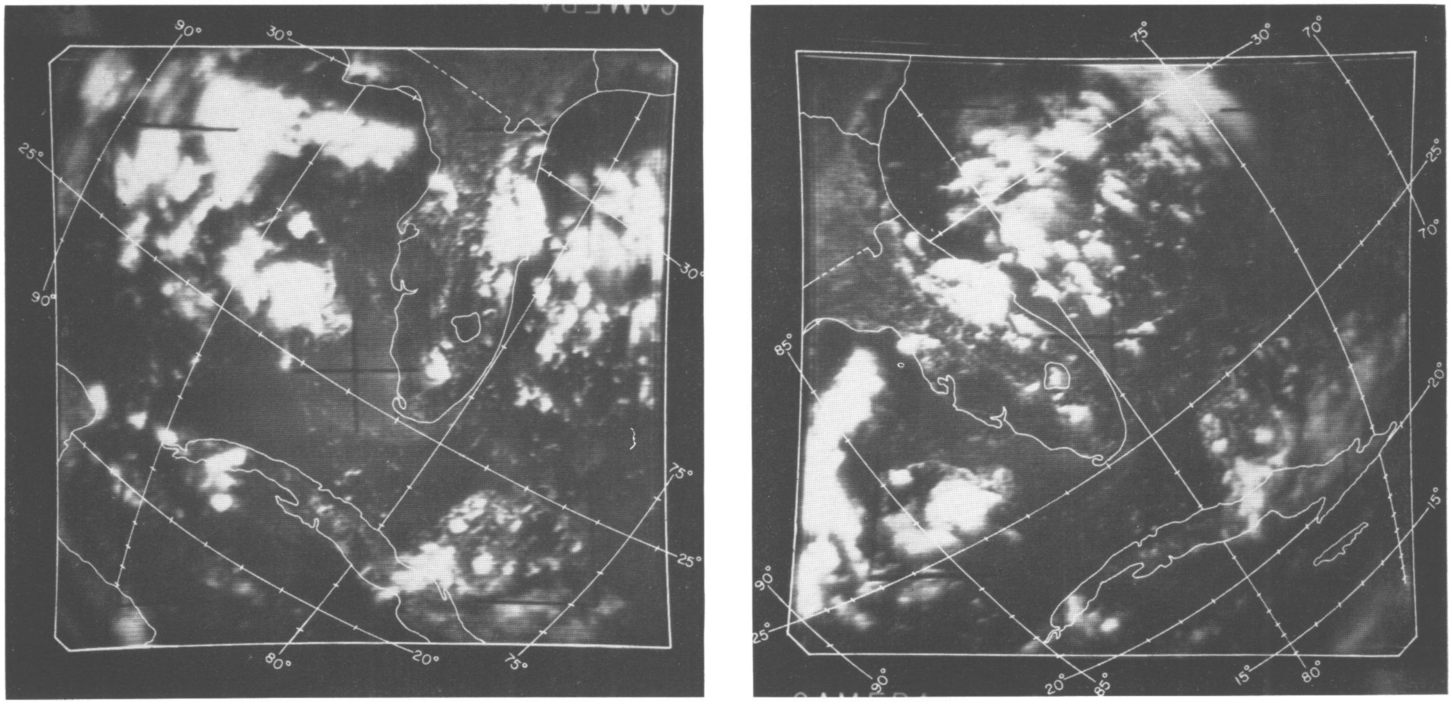
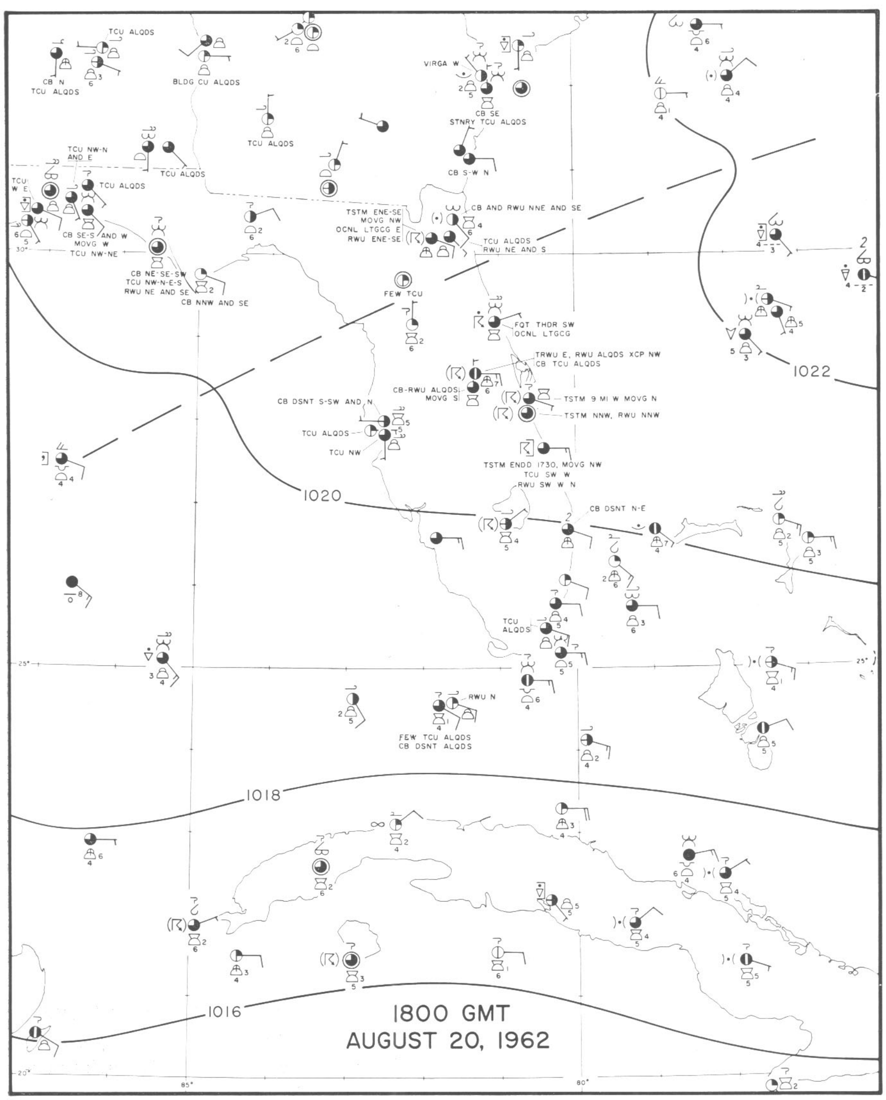


FIGURE 13.—TIROS V photographs (pass 892-direct, frames 6, left, and 7, right) taken at approximately 1750 GMT, August 20, 1962.



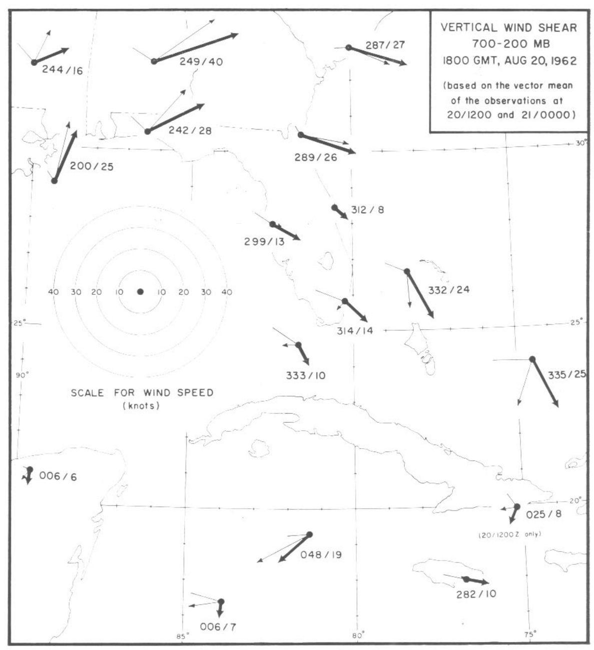


FIGURE 15.—Vectors for the 700-mb. wind (light lines), 200-mb. wind (light arrows), and the vertical shear for the 700–200-mb. layer (heavy arrows), for 1800 GMT, August 20, 1962. All vectors are vector means of the observations at 20/1200 GMT and 21/0000 GMT.

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FIGURE 14.—Surface map for 1800 GMT, August 20, 1962, including sea level isobars and plotted data (sky cover, wind, clouds, and present weather). Remarks pertaining to clouds and weather also are shown.

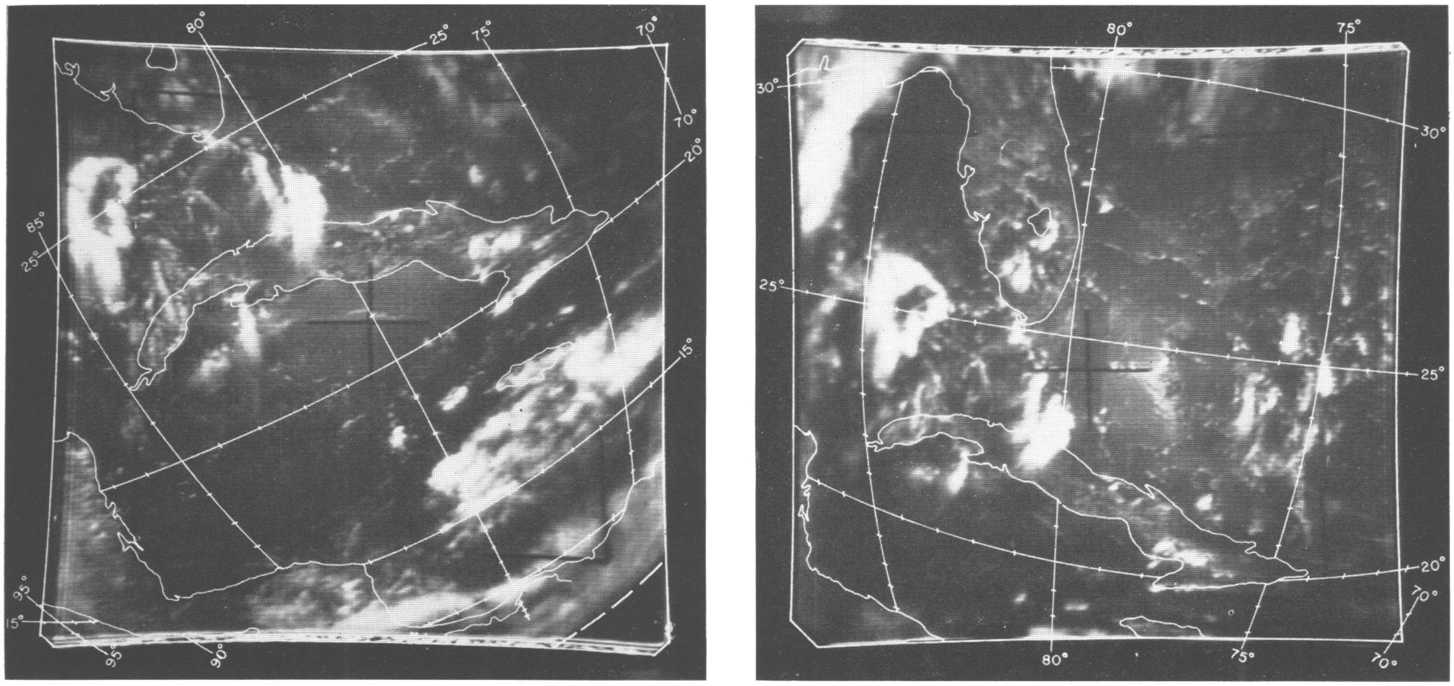
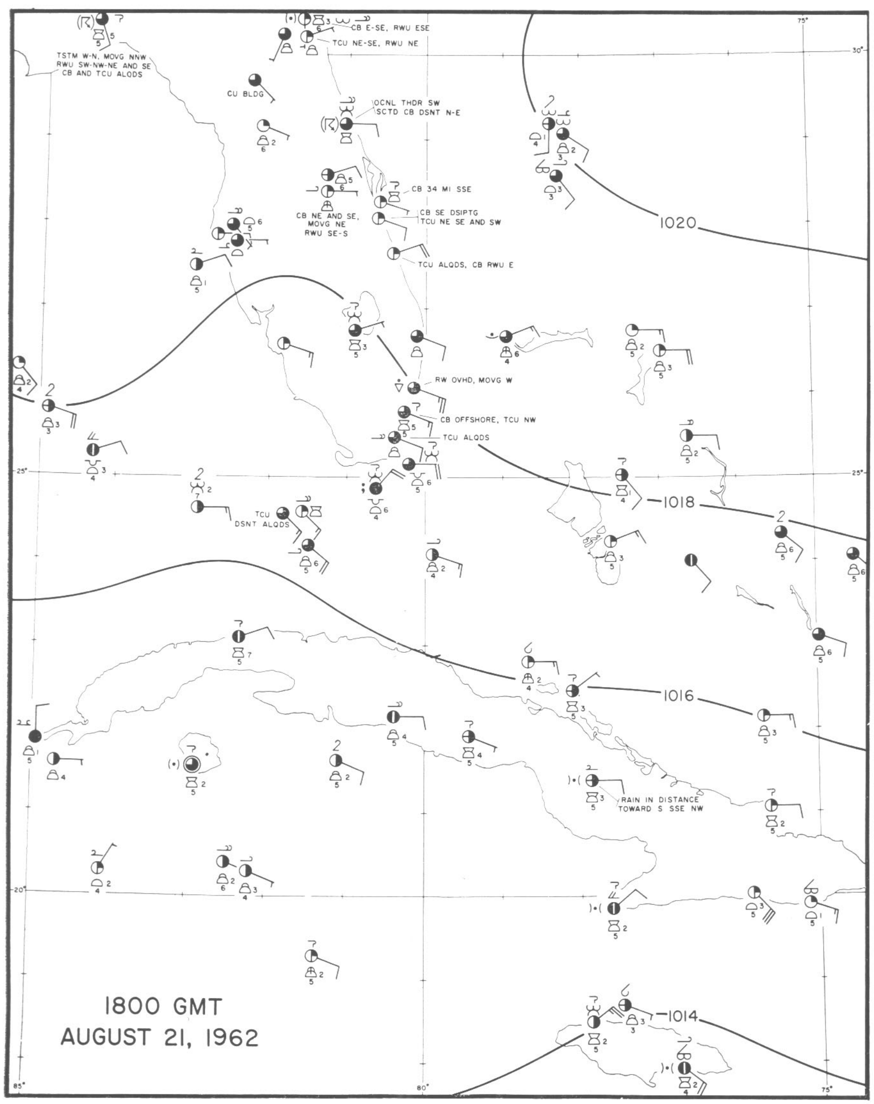


FIGURE 16.—TIROS V photographs (pass 906-direct, frames 3, left, and 5, right) taken at approximately 1715 GMT, August 21, 1962.



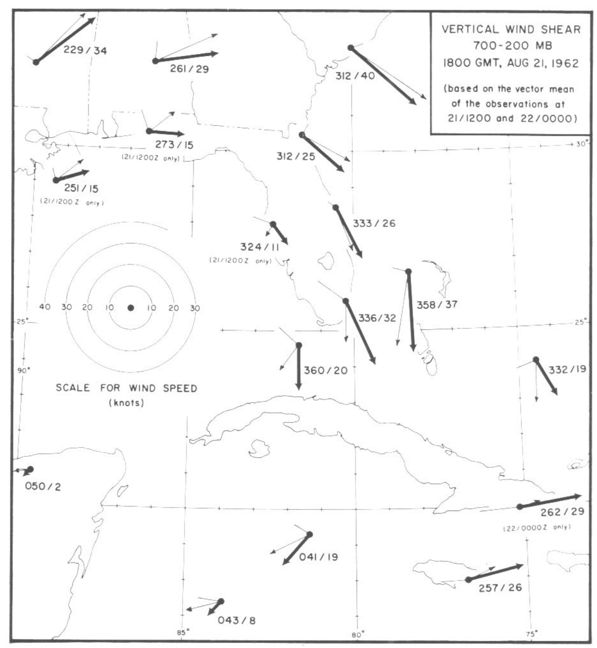


FIGURE 18.—Vectors for the 700-mb. wind (light lines), 200-mb. wind (light arrows), and the vertical shear for the 700–200-mb. layer (heavy arrows) for 1800 GMT, August 21, 1962. All vectors are vector means of the observations at 21/1200 GMT and 22/0000 GMT.

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FIGURE 17.—Surface map for 1800 GMT, August 21, 1962, including sea level isobars and plotted data (sky cover, wind, clouds, and present weather). Remarks pertaining to clouds and weather also are shown.

well with the 200-mb. winds, since directional differences between the shear and the 200-mb. wind are not large. This is particularly true over the area around western Cuba, where the plumes appear to be from the NNE. However, the generally larger magnitudes of the shears, compared to the 200-mb. winds, and the relatively long anvils observed by TIROS indicate that the shear probably is the more influential factor.

5. SUMMARY AND CONCLUSIONS

It is clear that cumulonimbus anvils are at least partially shaped by the environmental winds. It is not always so clear just what wind information is revealed in individual cases, but it seems that the direction of the vertical wind shear between the lower troposphere and the cirrus level is the parameter generally most nearly indicated by the anvil cloud orientation.

The interpretation of vertical shear would logically follow from the assumption that the main stem of the cumulonimbus moves with the lower-tropospheric mean flow. Internal forces also are known to affect storm movements, in ways that are not fully understood, and local topographic influences may exist, so that the assumption that the cumulonimbus cloud is carried along by the mean flow is only an approximation at best. However, there seems to be no reason to believe that it is not a useful approximation, particularly over large uniform areas. Deviations might be expected to occur in the vicinity of local terrain features such as islands, coasts, and mountain peaks.

In this study good general agreement was found between the anvil orientations and the direction of the vertical shear, but because of small differences between shear and upper-level winds there was often equally good agreement with the upper-level winds themselves. Therefore, a preference for shear, while believed to exist generally, has not been well established by these particular cases. A few instances favored the upper-level winds (e.g., the cloud south of Lake Okeechobee on August 20); such instances may have been due to a tendency for the main cloud to remain rooted to the low-level sea breeze convergence.

Although this investigation is rather limited, and the resolution of TIROS photographs precludes identification of all of the smaller mesoscale cloud features that one might wish to see, some tentative general conclusions may be justified:

(1) Both this and previous studies indicate that cumulonimbus and thunderstorm clouds not embedded in dense stratiform layers frequently appear as relatively small or medium-sized, irregular, bright masses in TIROS pictures. One or more sides of the individual masses may be rather sharp-edged and bordered by clear air.

(2) The orientation of the anvils and cirrus plumes of well-developed thunderstorm clouds may be used to indicate the direction of the vertical shear between lower-tropospheric and upper-tropospheric winds if it can be assumed that local influences on storm movement are negligible. Where there is reason to believe that the thunderstorms may tend to be stationary because of local topographic effects (e.g., mountain peaks, small heated islands), the orientation of the anvils will more nearly indicate the direction of the upper-level winds themselves than the direction of the vertical wind shear. In data-sparse areas, TIROS pictures of either of these situations might provide information about the upper-tropospheric flow not immediately obtainable from other sources.

(3) Pronounced anvils with long feathery downwind extensions and sharp upwind edges indicate relatively strong vertical shear or strong upper winds. This is a very qualitative inference and should be used with caution.

(4) Towering cumuli and small cumulonimbus clouds not yet producing anvils do not offer, in TIROS pictures, enough visible evidence of vertical shear to permit inferences about the upper-level winds. The apparent displacement of these clouds relative to coastlines, however, may indicate the direction of the lower-level flow.

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REFERENCES

1. H. R. Byers and L. J. Battan, "Some Effects of Vertical Wind Shear on Thunderstorm Structure," *Bulletin of the American Meteorological Society*, vol. 30, No. 5, May 1949, pp. 168–175.
2. H. R. Byers and R. R. Braham, Jr., *The Thunderstorm*, U.S. Weather Bureau, Washington, D.C., June 1949, 287 pp.
3. J. H. Conover, "Cloud Interpretation from Satellite Altitudes," *Research Note 81*, AFCRL–62–680, Air Force Cambridge Research Laboratory, Bedford, Mass., July 1962, 77 pp., and Supplement 1, May 1963, 19 pp.
4. C. O. Erickson and L. F. Hubert, "Identification of Cloud Forms from TIROS I Pictures," *MSL Report No. 7 to the National Aeronautics and Space Administration*, U.S. Weather Bureau manuscript, Washington, D.C., June 1961, 68 pp.
5. R. W. Fett, "TIROS V Views Final Stages in the Life of Typhoon Sarah, August 1962," *Monthly Weather Review*, vol. 91, No. 8, Aug. 1963, pp. 367–373.
6. T. Fujita, "A Review of Researches on Analytical Mesometeorology," *Research Paper* No. 8, Mesometeorology Project, Dept. of the Geophysical Sciences, The University of Chicago, Feb. 1962, 114 pp.
7. T. Fujita, "A Technique for Precise Analysis for Satellite Data; Volume I—Photogrammetry," *Meteorological Satellite Laboratory Report* No. 14, U.S. Weather Bureau manuscript, Washington, D.C., Jan. 1963, 106 pp.
8. T. Fujita, "Use of TIROS Pictures for Studies of the Internal Structure of Tropical Storms," *Research Paper* No. 25, Mesometeorology Project, Dept. of the Geophysical Sciences, The University of Chicago, October 1963, pp. 1–20.
9. T. Fujita, T. Ushijima, W. A. Hass, and G. T. Dellert, Jr., "Meteorological Interpretation of Convective Nephsystems Appearing in TIROS Cloud Photographs," *Research Paper*

No. 9, Mesometeorology Project, Dept. of the Geophysical Sciences, The University of Chicago, April 1962, 34 pp.

10. H. W. Hiser, H. V. Senn, and P. J. Davies, "Meso-Scale Synoptic Analysis of Radar and Satellite Meteorological Data," Final Report to the U. S. Weather Bureau under Contract No. Cwb-10242, The Marine Laboratory, University of Miami, Oct. 1963, 45 pp.
11. W. Hitschfeld, "The Motion and Erosion of Convective Storms in Severe Vertical Wind Shear," *Journal of Meteorology*, vol. 17, No. 3, June 1960, pp. 270–282.
12. W. Hitschfeld, "Plume Formation in Thunderstorms," Proceedings of the Cloud Physics Conference, Woods Hole, Massachusetts, June 3–5, 1959, *Geophysical Monograph* No. 5, American Geophysical Union, Washington, D.C., 1960, pp. 94–101.
13. M. G. H. Ligda, "The Horizontal Motion of Small Precipitation Areas as Observed by Radar," *Proceedings of the Third Weather Radar Conference*, McGill University, Montreal, Sept. 1952, pp. D41–48.
14. J. S. Malkus, "Effects of Wind Shear on Some Aspects of Convection," *Transactions of the American Geophysical Union*, vol. 30, No. 1, Feb. 1949, pp. 19–25.
15. J. S. Malkus, "The Slopes of Cumulus Clouds in Relation to the External Wind Shear," *Quarterly Journal of the Royal Meteorological Society*, vol. 78, No. 338, Oct. 1952, pp. 530–542.
16. E. S. Merritt, "Fleet Applications—Meteorological Operational Satellites (Tropics—Easterly Waves)," Final Report to the U.S. Navy Weather Research Facility under Contract No. 189(188)-56897A, ARACON Geophysics Co., Concord, Mass., December 1963, 45 pp.
17. C. W. Newton and S. Katz, "Movement of Large Convective Rainstorms in Relation to Winds Aloft," *Bulletin of the American Meteorological Society*, vol. 39, No. 3, Mar. 1958, pp. 129–136.
18. C. W. Newton and H. R. Newton, "Dynamical Interactions between Large Convective Clouds and Environment with Vertical Shear," *Journal of Meteorology*, vol. 16, No. 5, Oct. 1959, pp. 483–496.
19. Staff Members, NSSP, "Environmental and Thunderstorm Structures as Shown by National Severe Storms Project Observations in Spring 1960 and 1961," *Monthly Weather Review*, vol. 91, No. 6, June 1963, pp. 271–292.
20. L. F. Whitney, Jr., "Another View from TIROS I of a Severe Weather Situation, May 16, 1960," *Monthly Weather Review*, vol. 89, No. 11, Nov. 1961, pp. 447–460.
21. L. F. Whitney, Jr., "Severe Storm Clouds as Seen from TIROS," *Journal of Applied Meteorology*, vol. 2, No. 4, Aug. 1963, pp. 501–507.
22. L. F. Whitney, Jr. and S. Fritz, "A Tornado-Producing Cloud Pattern Seen from TIROS I," *Bulletin of the American Meteorological Society*, vol. 42, No. 9, Sept. 1961, pp. 603–614.

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